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Comparison of Transesophageal Echocardiographic and Scintigraphic Estimates of Left Ventricular End-Diastolic Volume Index and Ejection Fraction in Patients Following Coronary Artery Bypass Grafting

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Transesophageal echocardiography (TEE) has become a commonly used monitor of left ventricular (LV) function and filling during cardiac surgery. Its use is based on the assumption that changes in LV short-axis ID reflect changes in LV volume. To study the ability of TEE to estimate LV volume and ejection immediately following CABG, 10 patients were studied using blood pool scintigraphy, TEE, and thermodilution cardiac output (CO). A single TEE short-axis cross-sectional image of the LV at the midpapillary muscle level was used for area analysis. Between 1 and 5 h postoperatively, simultaneous data sets (scintigraphy, TEE, and CO) were obtained three to five times in each patient. End-diastolic (ED_a) and end-systolic (ES_a) areas were measured by light pen. Ejection fraction area (EF_a) was calculated ($EF_a = (ED_a - ES_a)/ED_a$). When EF_a was compared with EF by scintigraphy, correlation was good ($r = 0.82$ SEE $= 0.07$). ED_a was taken as an indicator of LV volume and compared with LVEDVI which was derived from EF by scintigraphy and CO. Correlation between ED_a and LVEDVI was fair ($r = 0.74$ SEE $= 3.75$). The authors conclude that immediately following CABG, a single cross-sectional TEE image provides a reasonable estimate of EF but not LVEDVI. (Key words: Anesthesia: cardiac. Heart: LVEDVI; ejection fraction. Monitoring: transesophageal echocardiography. Surgery: cardiac; CABG.)

TRANSESOPHAGEAL ECHOCARDIOGRAPHY (TEE) has been used to estimate left ventricular (LV) filling and ejection in patients undergoing cardiac surgery. This use of TEE is based on the findings of a number of investigators who have shown that despite a variety of loading conditions, changes in LV short-axis ID reflect changes in LV volume.[1-3] From these observations one might expect changes in short-axis area, readily measured by TEE, to mirror changes in LV end-diastolic volume index (LVEDVI). Recently, Konstadt *et al.* demonstrated that epicardial echocardiographic measurements correlate well with transesophageal echocardiographic measurements of LV short-axis area.[4] These investigators concluded that TEE "can accurately assess left ventricular filling and ejection."[4] However, a major criticism of these studies has been that TEE measurements have not been compared with those from a recognized standard such as cine angiography or gated pool scintigraphy.[5] The goal of this study was to evaluate the ability of area measurements by TEE to estimate LVEDVI or ejection fraction (EF) in patients immediately following coronary artery bypass grafting (CABG) using accepted standards for measurement of volume and ejection.

Materials and Methods

PATIENT SELECTION

With approval from the Committee on Human Research at the University of California, San Francisco, patients scheduled to undergo CABG were asked 1 day prior to surgery to participate in the study. Those who gave informed consent and in whom a clinical decision was made to insert a pulmonary artery catheter were enrolled in the study. The decision to insert the catheter was left to the discretion of the attending anesthesiologist and surgeon. No attempt was made to control the anesthetic technique employed. Of the 14 patients enrolled in the study, four were excluded. One patient died intraoperatively. Adequate short-axis LV images could not be obtained in two patients. Another patient was too hemodynamically labile to study. Of the ten patients studied one had an aortic valve replacement while another underwent resection of a small LV aneurysm in addition to CABG.

The final patient group included ten male patients ages 41–75 yr. Weight ranged from 55–106 kg. All patients were studied 1–5 h postoperatively in the intensive care unit (ICU). Patients' lungs were mechanically ventilated

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with tidal volumes of 12–15 ml/kg. Five centimeters of H_2O positive end-expiratory pressure (PEEP) was used in all patients except the patient who underwent both CABG and aneurysectomy who received up to 10 cm H_2O of PEEP. Respiratory rate was adjusted to maintain a *p*H of 7.40–7.45. Inspired oxygen concentration was adjusted according to the standard ICU protocol. Using this protocol, Pa_{O_2} was consistently greater than 100 mmHg during the study period. Sedation was left to the discretion of the physicians caring for the patients in the intensive care unit.

TRANSESOPHAGEAL ECHOCARDIOGRAPHY

After induction of anesthesia, a Diasonics™ 3.5-MHz phased array ultrasonic transducer, fitted to the end of a standard gastroscope, was inserted into the esophagus. Either a Diasonics™ 3400 or 6400 ultrasonograph was used for two-dimensional echocardiographic imaging during and after surgery. Upon completion of surgery the probe remained in place.

Upon arrival in the ICU the probe was positioned to obtain a LV short-axis image at the midpapillary muscle level. Whenever possible, the TEE transducer was not moved during the study. If repositioning was required to obtain an adequate image, every attempt was made to duplicate the original image. An experienced reviewer, unaware of any other data, viewed all TEE images and deleted images of poor quality and those felt not to represent identical cross-sectional images.

Area analysis of TEE data consisted of measurement of end-diastolic area (ED_a) and end-systolic area (ES_a). Areas were determined for three consecutive beats by outlining the endocardium with a light pen using the leading-leading edge technique. The accuracy of this approach for area determination has been demonstrated by other investigators.[6] The area analysis of TEE images was done in a blinded fashion with the reviewer unaware of the gated pool ejection fraction or the hemodynamic data. Two reviewers examined the data independently to test interobserver variability. The reviewers were unaware of any clinical data or results from other observers. Six measurements of ES_a were excluded because the ventricular cavity could not be outlined during systole. Two measurements of ED_a were not included because the left ventricular cavity size extended beyond the limits of the sector on the video screen. Overall, 37 of 39 images (95%) at end-diastole, and 34 of 39 images (87%) at end-systole were analyzed. Patient data are presented in table 1.

For analysis of segmental wall motion the TEE short-axis cross-sections were divided into quadrants using the papillary muscles as reference points. This approach compensates for changes in rotation and translation. Segmental wall motion analysis was performed as previously described by Smith *et al.*[7] "The cross sectional image was divided into quadrants with the papillary muscles as guides. A segment was considered to contract normally if an imaginary radius to the center of the left ventricle shortened by more than 30% and the wall thickened considerably. Mild hypokinesis was considered to occur if shortening of the radius was less than 30% but more than 10% and the wall thickened. Severe hypokinesia was diagnosed if the wall thickened minimally and radial shortening was less than 10%. An akinetic segment was defined as one in which the wall did not thicken during systole, and a dyskinetic segment as one in which the wall bulged and thinned during systole."[7] The first echocardiogram was used as the baseline and segmental wall-motion abnormalities (SWMA) were defined as occurring if a segment worsened by two or more classifications in the absence of global wall-motion changes. Patients were categorized as having or not having SWMA at the onset of the study. A segment with severe hypokinesis or worse was defined as a SWMA at the start of the study. New SWMA that developed during the course of the study were also noted (table 2). Segmental wall-motion analysis was performed by an experienced observer who was blinded to other data.

GATED POOL SCINTIGRAPHY

Gated pool scintigraphy was performed according to established techniques.[8–11] Thirty minutes before the first data acquisition period, 5 mg of stannous pyrophosphate was administered intravenously to each patient. Immediately prior to gated pool imaging, 5 ml of blood were withdrawn, labelled with 25 mCi of technetium-99 (Tc-99m) and reinjected. A Siemens portable scintillation camera, LEM, equipped with a 20-degree parallel slant-hole collimator was then positioned over the patient's chest to obtain the left anterior oblique (LAO) view that most clearly defined the interventricular septum. Electrocardiogram gated scintigraphy was then performed from three to five times during the study period. Camera angle was constant. Imaging was conducted in the best septal LAO projection for the time it took to acquire 6,000,000 counts. The photopeak was centered at that of Tc-99m, 140 keV, with the application of a 20% energy window. Data were stored on a hard disk.

Left ventricular regions of interest were generally derived automatically by a computer algorithm that identifies the moving ventricular edge. The program searches along multiple radii drawn from the ventricular center of counts, from the steepest fall in ventricular radioactivity to its plateau or subsequent rise at the edge of an adjacent

TABLE 1. Patient Data

Patient	Study	ED_a	ES_a	EF_{gp}*	EF_a	LVEDVI
1	1	19.1	10.1	0.41	0.47	62.7
1	2	16.3	7.8	0.45	0.52	78.7
1	3	25.4	13.1	0.38	0.48	89.3
2	1	9.7	4.9	0.74	0.49	—
3	1	14.3	9.6	0.34	0.33	67.4
3	2	18.2	10.9	0.4	0.4	49.0
3	3	24.1	15	0.37	0.38	74.0
3	4	25	16.2	0.34	0.35	66.6
3	5	21.1	15.5	0.28	0.27	70.9
4	1	24	14.6	0.33	0.39	55.5
4	2	24.7	16.6	0.3	0.33	59.2
4	3	27	16.1	0.37	0.4	70.7
4	4	27.2	18.4	0.33	0.32	86.9
5	1	7.6	3.9	0.74	0.49	16.6
5	2	11.2	4.6	0.7	0.59	21.1
5	3	12.4	5.5	0.65	0.56	25.0
5	4	12.2	5.8	0.67	0.52	24.3
5	5	10.6	5.8	0.69	0.45	24.8
6	1	19.5	13.4	0.26	0.23	94.0
6	2	24.1	16.7	0.32	0.38	88.6
6	3	19	13.6	0.32	0.28	91.8
6	4	18.9	14	0.26	0.26	102.1
6	5	23.6	16.1	0.27	0.32	112.5
6	6	21.1	15.5	0.29	0.27	90.2
7	1	12.8	7.2	0.46	0.44	46.6
7	2	16.7	7.8	0.66	0.53	33.5
7	3	14.8	7.1	0.63	0.52	34.3
7	4	12	6.3	0.69	0.48	31.6
8	1	14.8	—	0.54	—	49.1
8	2	13.1	—	0.52	—	48.4
8	3	14.8	—	0.38	—	59.4
9	1	21.5	9.7	0.51	0.55	—
9	2	24.4	11	0.44	0.55	—
9	3	25.1	11	0.44	0.56	—
10	1	10.9	4.3	0.8	0.61	38.8
10	2	13.9	5	0.75	0.64	22.7
10	3	15.1	6.5	0.8	0.57	28.6

* EF_{gp} = Ejection fraction by gated pod scintigraphy.

chamber or extracardiac organ. The points on these multiple radii subscribe two edges in each frame, one surrounding an inner region that underestimates the LV and an outer region that overestimates it. Regional background is calculated from local count variations within the zone between these edges in the end-systolic frame and is subtracted from perceived ventricular counts in all frames. This method compares well with other automated methods but is likely superior to them owing to its choice of a nonuniform background value. When visually departing from the ventricular boundary, the edges can be corrected, or alternatively, diastolic and systolic edges can be drawn manually with a fixed-background region according to the conventional method. The latter was required in four patients studied here. Given the ventricular edges for diastolic and systolic frames and the background correction, the LV ejection fraction is calculated from the conventional relationship: EF = (LVEDC − LVESC)/(LVEDC − B), where B = background counts, LVEDC = left ventricular end-diastolic counts, LVESC = left ventricular end-systolic counts, and EF = left ventricular ejection fraction.

From past evaluation in the radiopharmacy at UCSF and in the performance of these serial patient studies, labeling efficiency generally exceeds 90% on initial radionuclide administration and has been found to persist at levels above 80% for the duration of the study. This was confirmed in the patients studied here. Blood samples taken from every patient at the time of acquisition confirmed continued adequate blood pool labeling. As in studies shown extensively through the literature, the target to background radioactivity ratios generally lie in the range of 2–4/1. This was also the range noted in this study.

Gated pool scintigraphy derived values for EF have been shown to correlate well with results from contrast angiography (r = 0.85).[8] In this institution the 95% confidence interval of left ventricular ejection fraction is 9%

TABLE 2. Segmental Wall Motion Analysis and Reoperation as Related to the Presence of Discordant Changes When Comparing LVEDVI with ED_a

Patient	Operation	Discordant Changes	Preoperative SWMA	New SWMA	Redo
1	CABG	−	−	−	−
2	CABG	+	−	+	−
3	CABG	−	−	−	−
4	CABG	−	−	+	−
5	CABG	−	−	−	−
6	CABG	+	−	−	−
7	CABG	+	−	−	+
8	CABG	−	−	−	−
9	CABG + AVR	+	−	−	−
10	CABG+ ANEURYSECTOMY	−	−	−	−

SWMA = segmental wall motion abnormalities. REDO = repeat operation.

Discordant change implies a change in ED_a of 15% or more accompanied by a change in LVEDVI of 15% or more in the opposite direction.

and the normal LV ejection fraction is 0.67 ± 0.12 (SD), with intraobserver variability of ±0.04.

Gated pool scintigraphic calculations were performed in a blinded fashion, with the reviewer unaware of any other patient data. In two patients the nuclear medicine data are incomplete due to a computer malfunction.

THERMODILUTION CARDIAC OUTPUT

Simultaneous measurement of cardiac output (CO) was used to derive LVEDVI by dividing CO by heart rate and EF by scintigraphy. Ten milliliters of saline were injected, and the boluses repeated until three consecutive values for CO within 10% of the mean were obtained. An American Edwards®, 7-F TD AEL Swan Ganz catheter and an American Edwards® cardiac output computer, Model 9520A were used for CO measurements. Respiration was halted, but PEEP maintained, during determination of CO to eliminate respiratory variation in CO calculated from data derived from six to eight ventricular contractions. CO by thermodilution done in this manner correlates well with other techniques such as dye dilution, producing a 95% confidence interval of 9%.[12] Validation of this technique for determination of LVEDVI has been done by other investigators.[13] A 95% confidence level of 11.4% has been determined for the calculated LVEDVI.[13] A pulmonary artery catheter could not be inserted in one patient and LVEDVI could not be calculated in that patient.

STUDY PROTOCOL

Patients were transferred to the ICU immediately upon completion of surgery. Approximately 1 h after arrival in the ICU the first measurements were made. During each data acquisition period, simultaneous TEE, scintigraphic, and CO measurements were obtained. After the start of the gated blood pool acquisition, TEE images were recorded for 20–30-s periods at the beginning, middle, and end of the acquisition period. Respiration was halted, but PEEP maintained, during the 20–30 s necessary to record TEE images and determine cardiac output. Patients had from three to five data acquisition periods between 1–5 h after arrival in the ICU.

ANALYSIS

Interobserver variability was examined using linear regression to compare area measurements of identical images from two observers.

End-diastolic area was compared with LVEDVI by linear regression. Ejection fraction area (EF_a) was derived using the equation $EF_a = (ED_a - ES_a)/ED_a$ then compared with EF by gated pool using linear regression.

Both ΔEF *versus* ΔEF_a and ΔLVEDVI *versus* ΔED_a were examined within individual patients for discordant changes. A discordant change was defined as a change of 15% or more in one parameter accompanied by a 15% or greater change in the other parameter in the opposite direction. All other changes were concordant.

Results

All patients tolerated the study well. There were no clinically apparent responses to probe insertion or manipulation in these patients who were heavily sedated, and whose lungs were mechanically ventilated. No complications from TEE, nor from any other measurement technique were noted.

Interobserver variability was small when comparing identical TEE images. When comparing identical end-diastolic areas, interobserver correlation was excellent ($r = 0.98$, SEE = 1.19, $P < 0.0001$). Comparison of end-systolic areas also demonstrated excellent correlation ($r = 0.98$, SEE = 0.99, $P < 0.0001$). Interobserver variability for measurement of EF_a was also good ($r = 0.89$, SEE = 0.06, $P < 0.0001$).

Comparison of ED_a with LVEDVI yielded a correlation coefficient of 0.74 ($r = 0.74$, SEE = 3.75, $P < 0.0001$) (fig. 1). When comparing ΔED_a with ΔLVEDVI, discordant changes were observed in three of eight patients undergoing CABG alone. They occurred with a frequency of three per 19 comparisons (17%). No patient had more than one discordant change.

When comparing EF with EF_a, a correlation coefficient of 0.82 was calculated ($r = 0.82$, SEE = 0.07, $P < 0.0001$) (fig. 2). Twenty-one comparisons of ΔEF with ΔEF_a were made in eight patients. No discordant changes were noted when comparing EF_a with EF. EF_a was not consistently higher or lower than EF.

In the patient who underwent CABG and AVR, discordant changes were seen when comparing ED_a with LVEDVI. Two comparisons were made and both demonstrated discordance. When comparing EF with EF_a no discordant changes were noted. A PA catheter could not be inserted in the patient who had an aneurysectomy in addition to CABG, and LVEDVI could therefore not be calculated. EF *versus* EF_a did, however, demonstrate concordance.

In an attempt to determine the cause of the discordance noted between LVEDVI and ED_a, we looked for preoperative SWMA, new SWMA that developed during the study, and whether or not the patient was undergoing repeat surgery. No factor was consistently related to the development of discordant changes (table 2).

Discussion

This study was designed to assess the ability of TEE to either qualitatively or quantitatively estimate LV filling and ejection in patients who were sedated and whose lungs were being mechanically ventilated immediately following CABG. These patients were chosen because the limitations of interpretation of pulmonary artery catheter pressure data in this group are well documented,[14] while the need for information about LV function and volume in these critically ill patients is great. Unlike previous studies, TEE measurements were compared with those obtained by recognized standards of volume and ejection measurement. And unlike most echocardiographic studies, all measurements (CO, TEE, and SCINT) were made simultaneously. Finally, serial measurements were made, providing information on the ability of TEE to follow changes in filling and ejection in an individual patient.

In this patient population it was found that TEE derived ED_a correlated reasonably well with LVEDVI. The correlation found between LVEDVI and ED_a is consistent with that from previous studies.[15,16] Of major importance, however, are the discordant changes that were noted when comparing ΔLVEDVI with ΔED_a. Previous studies have not obtained serial measurements for a single patient so the accuracy of serial measurements of cross-sectional area as indicators of changes in LVEDVI has not been previously addressed. Probably the major factor responsible for the presence of discordant changes is the use of a single cross-sectional area to estimate volume. The limitations of a single view for estimating volume have been repeatedly demonstrated and a better correlation is probably not possible using only a single cross-sectional area to estimate volume.[16–19] It is clear from both the numerous mathematical models employed to determine the best approach to echocardiographic estimation of left ventricular volume, as well as numerous clinical investigations, that the accuracy of volume estimates increases as one increases the number of cross-sections imaged and in addition take into account long-axis changes.[20] The restrictions imposed by imaging from the esophagus with the instrumentation now available limit the number of views that can be obtained and therefore the reliability of the technique for volume estimation.

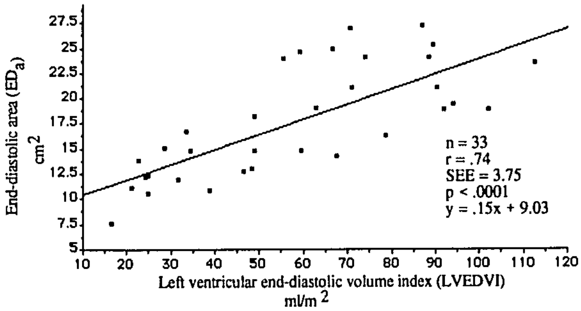

FIG. 1. Left ventricular end-diastolic volume index, derived from ejection fraction by gated pool scintigraphy and thermodilution cardiac output, compared with left ventricular end-diastolic area by TEE in eight patients.

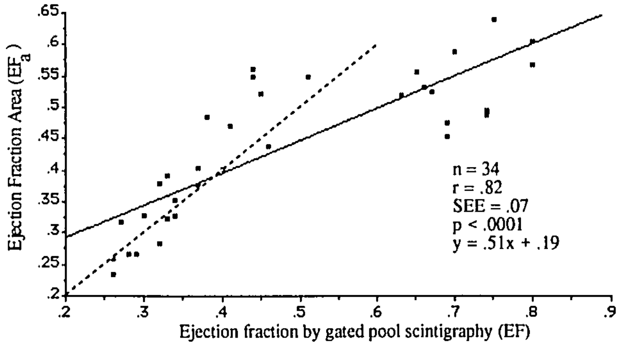

FIG. 2. Ejection fraction by gated pool scintigraphy compared with ejection fraction area determined by transesophageal echocardiography in nine patients. The dashed line is the line of identity.

Additional reasons for the lack of a stronger correlation and for the discordant changes are errors in measurement. Since measurement of LVEDVI requires both gated pool scintigraphy and thermodilution cardiac output, errors may be compounded. Previous studies have demonstrated that the 95% confidence interval for LVEDVI determined with these techniques is 11.4%, suggesting that measurement error alone is not responsible.[13]

Other factors that may weaken the correlation between LVEDVI and ED_a are mitral regurgitation (MR), SWMA, and changes in ventricular function induced by cardiopulmonary bypass (CPB). Recent studies using transesophageal Doppler color flow mapping suggest that MR is common in this patient population.[21],§§ In the presence

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§§ Cahalan M. K.: unpublished data.

of MR, thermodilution tends to underestimate stroke volume compared with that derived from angiographic techniques.[22] Changes in regurgitant volume could change the apparent stroke volume as determined by thermodilution and thus change the calculated LVEDVI. Although the magnitude of the MR cannot be quantitatively determined at this time this clearly deserves further study. SWMA may also be a factor.[18] SWMA were noted in only two of our patients, but it is conceivable that SWMA were occurring in parts of the ventricle not imaged by TEE. Geometric alterations of the ventricle due to these SWMA could alter our basic assumption that most of the volume change occurring in the ventricle occurs in the short axis and make a single cross-section less representative of ventricular function. Changes in ventricular physiology induced by CPB may also contribute to changes in contraction not adequately reflected by a single short-axis view of the left ventricle. Although it is clear that CPB and cardioplegia alter ventricular function, sensitive studies of contraction patterns have not been done, particularly during the immediate postbypass period. Any or all of these factors may have weakened the correlation between LVEDVI and ED_a.

When comparing EF with EF_a, correlation was better ($r = 0.82$, $SEE = 0.07$, $P < 0.0001$) than it was between LVEDVI and EF_a. The lack of an even stronger correlation is due to the factors previously discussed.

The data suggest that although TEE does reflect LV filling in this group of patients, TEE estimates of LV volume for any individual patient may be unreliable at the same time. The presence of discordance cannot be predicted. Moderate changes in LV volume are not consistently reflected by changes in cross-sectional area after CABG. This study does not, however, suggest that TEE estimates of volume are without value. TEE can be used to determine if the heart is empty or full, states that represent rather large differences in volume. Furthermore, even in this patient population, TEE reliably assesses directional change in EF. Finally, we wish to stress that the results of this study apply to patients immediately following CABG and should not be extrapolated to patients undergoing other surgical procedures.

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